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Air gauges as a part of the dimensional inspection systems

Miroslaw Rucki [a], Branimir Barisic [b,*], Gyula Varga [c]

[a] Poznan University of Technology, Institute of Mechanical Technology, Poznan, Poland
[b] University of Rijeka, Faculty of Engineering, Rijeka, Croatia
[c] University of Miskolc, Faculty of Mechanical Engineering, Miskolc, Hungary

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A B S T R A C T

Air gauges for dimensional measurement are known for decades. They have been applied in many technological processes, especially in the systems of in-process control. The air gauges are connected with pneumatic measuring devices able to generate control signals. Nowadays, however, it is not enough to just indicate dimensional bounds of tolerance. The Quality Management Systems require recorded and processed data achieved during the measurement. Investigations led to the development of air gauges integrated with piezoresistive pressure transducers. In those systems the results of measurement are achieved in digital form, they are processed and recorded. Additionally, dynamical properties of integrated air gauges appear much better. Multipoint linearization of the air gauge appears to be advantageous, though some companies offer the adjustment using one setting master only.

1. Introduction

Nowadays, the rising demands on accuracy of the produced details require continuous improvement of metrological properties of the measuring tools. In many cases it seems impossible to improve the metrological properties of air gauge, because its measuring range depends on the sensitivity. The higher is sensitivity, the shorter is the measuring range, and vice versa. However, there are also many merits of the pneumatic length measurement like the simple construction of gauge, cheap maintenance, easy regulation of multiplication and measuring range, non-contact measurement, no sliding members, self-cleaning of the measured surface with the outflowing air (in open jet devices), averaging and combining capabilities, adaptability to multiple dimension gauging and so on [1]. Those advantages cause still high interest of industrial enterprises in this kind of measuring tools. Though nowadays advantageous measuring methods are developed, air gaging is still irreplaceable in many applications, especially in in-process control [2] and in unconventional measurements like measurement of extremely long microbores [3].

2. Air gauging principle

Typically, dependent on the utilized property of the pressured air, the air gauges operational principles could be based on the flow (velocity) or pressure (back-pressure) [1]. The most widely used are the ones of back-pressure described below.

Typical pressure air gauge works as a flapper-nozzle valve, shown in Fig. 1. The pressure p_k in the measuring chamber depends on the slot width s between the head of the measuring nozzle and the surface of the measured detail. Thus, the dimensions of measured detail could be indicated by the variations of the back-pressure p_k.

There is no exact linear relation between the air pressure p_k and the slot s. Fig. 2 presents the graph of the pressure in the measuring chamber versus the slot width $sp_k = f(s)$. Some part of the graph is proportional (marked z_p), and it is treated as a measuring range. The displacement s should be small enough in relation to the nozzle opening, in order to effectively reduce the

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* Corresponding author. Tel.: +385 51651489; fax: +385 51651465.
E-mail address: barisic@riteh.hr (B. Barisic).

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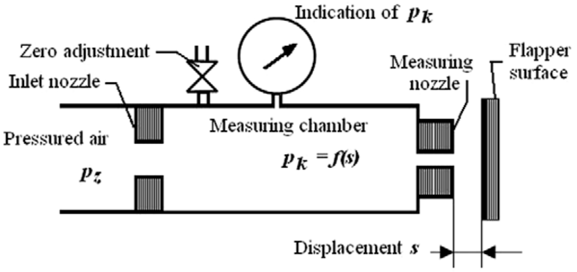

Fig. 1. An example of the air gauge.

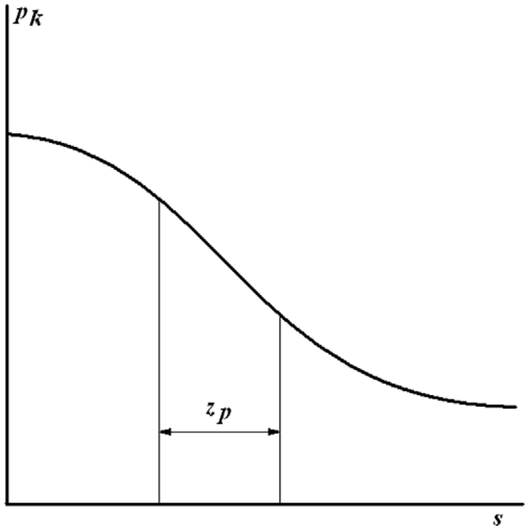

Fig. 2. Typical graph of the back-pressure $p_k = f(s)$.

air escape area. It had been derived from the theoretical limit of an effective restriction, that displacement should be $s = d/4$ [1].

To measure the pressure in a chamber of the air gauge, various methods could be applied. In the industrial dimensional inspection with the air gauges, there are still in use even the water manometers designed for lower range of pressures. However, because of limitations in conversion of the measurement signal from liquid column into digital one, this type of back-pressure measurement is going to be replaced completely by other methods.

Pressure transducers are actually a hybrid sensor-transducers. The primary sensor is usually an elastic element that deforms or deflects under the pressure (Fig. 3) [4]. A secondary transducer element converts the elastic element deflection into an electrical signal (voltage) or mechanical (rotation of a pointer). From the dimensional measurement point of view, mechanical signal is useful only for indication or at least for dimensional tolerance switch. If the device is to be included into the Quality Management System, it must be converted to electrical signal anyway.

The maximum elastic deflection of a uniformly loaded, circular diaphragm supported about its circumference occurs at its center and can be estimated by [4]:

$$y_{\max} = \frac{3(p_1 - p_2)(1 - v_p^2)r^2}{16E_m t^3}, \tag{1}$$

where $p_1 - p_2$ is the difference of pressure on both sides of diaphragm, v_p is the Poisson's ratio for the diaphragm material, r is the radius of the diaphragm, E_m is the bulk modulus and t is the thickness of the diaphragm.

The limitation of the diaphragms is small range of the deflection. The diaphragm should be selected so as its deflection would not exceed one-third of the diaphragm thickness. Therefore the most common method of converting diaphragm displacement into a measurable signal is based on strain gauges. Corrugated diaphragms could have larger range of displacement and could be equipped with mechanical amplifying device as it is shown in Fig. 4.

Other elastic elements provide displacement large enough to convert it into a rotation of a pointer. Example of the Bourdon tube used in the air gauge is shown in Fig. 5. Typically, the device is scaled in micrometers, so there is no need of recalculation of the results of pressure measurement into dimensional units.

Commonly, Bourdon tube gauges have instrument uncertainties on the level of 0.5–2% of the full-scale deflection of the gauge, but the best ones could reach as low uncertainty as 0.1% [4].

3. Pneumo-electric control devices and pneumo-electronic converters

In the industrial measurement, the result of the measurement is used for records of the measured sizes. It may be also indicated by lights when the set bounds are exceeded, or in feeding back systems the size control adjustments on the machine tool elements could be actuated. Therefore in most cases mechanical signal is converted into electrical one.

In order to obtain the electrical initiating signal from the air gauge, the elastic pressure sensor should be equipped with a proper element. One of the typical high-pressure pneumo-electric devices used for decades for the comparative dimensional measurements in manufacturing processes, is Aeropan B0-IX. It is able to generate electric signal output for signaling and control units. Its operation is based on the measurement of back-pressure p_k. Pneumatic measuring force within the measuring range is from 0.55 up to 1.15 kG/cm^2. The operation principle of the device is shown in Fig. 6 [5]. The pressured air p_z comes from the compressor through the reduction valve (1), fine filter (2), pressure stabilizer (3), and inlet nozzle with changeable diameter (4). The measuring nozzle (5) is placed in front of measured detail surface (6) in open jet plugs, or in front of flapper surface in general. Manometer (7) registers the changes of back-pressure p_k caused by the displacement s, closely connected with dimensions of measured detail.

Usually, two master rings, corresponding with upper and lower dimensional tolerances, are used for adjustment. The multiplication and the measuring range of the device could be adjusted through the regulators of inlet nozzle (4) and zero point (8), setting known values for each master. The Aeropan B0-IX ensured the measurement with

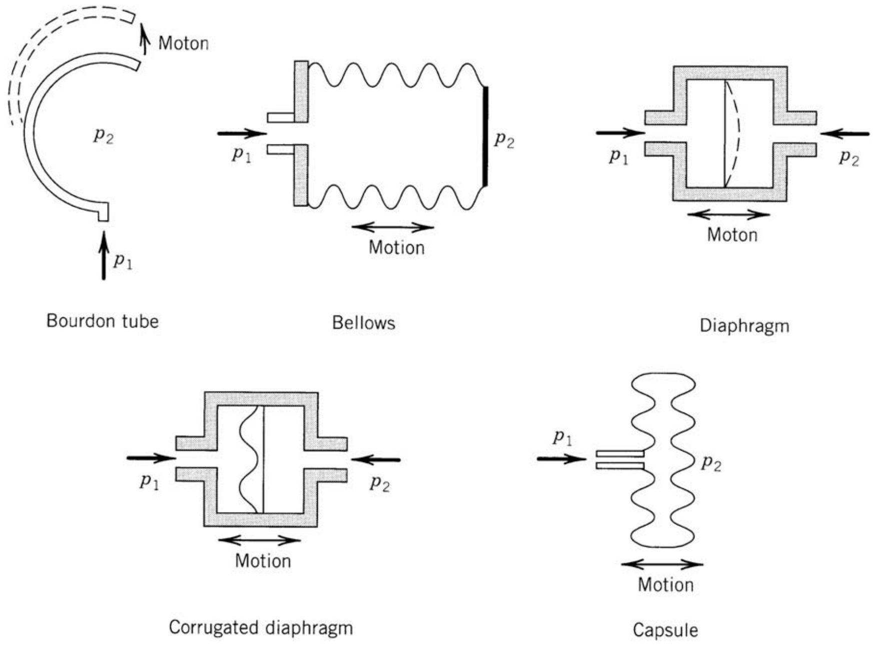

Fig. 3. Elastic elements used as pressure sensors [4].

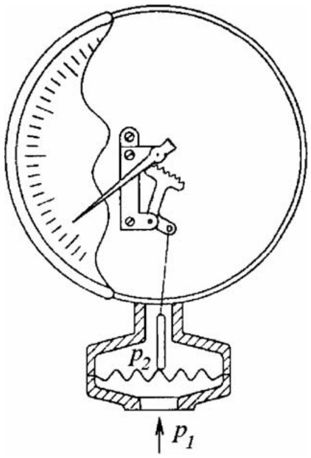

Fig. 4. Example of a mechanical secondary transducer.

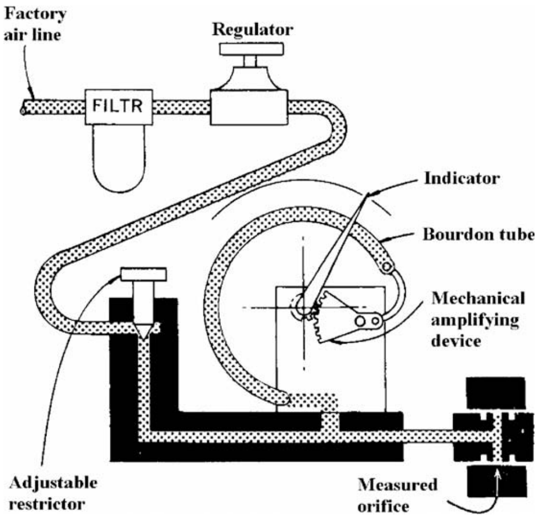

Fig. 5. Operating principle of an air gauge with a Bourdon tube [1].

resolution of 1, 2, 5, 10 μm dependent on the measuring range and multiplication (for wider ranges the resolution and multiplication are lower).

The bellows (9) are connected with adjustable electrical switchers (10) corresponding with a bounding dimensions. Usually those dimensions correspond with tolerances or selection groups or other bounds designed to initiate and to sustain desired processes. The exceeded bounds are indicated by the lights (11). The electrical connections are shown in Fig. 6 (right). The device ensure measurement with maximal inaccuracy of ±1 scale interval.

To gain the electronic signal from the pressure measurement, many methods are available [4]. Apart of the mentioned strain sensors placed directly to the diaphragm, capacitance properties of diaphragm could be used. When one or more fixed metal plates are placed directly above or below a metallic diaphragm, a capacitor is created that forms an effective secondary element. Also, the diaphragm may be in touch with the tip of inductive sensor like in the solution proposed by Nieberding company [6]. Here, the inductive sensor is fixed in front of the membrane, its tip in contact with the membrane, and it generates electronic output signal as an independent pressure/electronic converter. It may be connected to the measuring column or to the computer for further signal processing (Fig. 7).

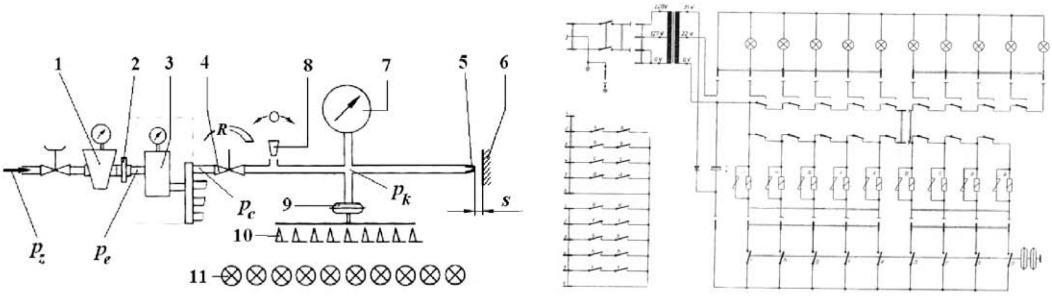

Fig. 6. Operation principle of Aeropan B0-IX (left) and its switching scheme (right) [5].

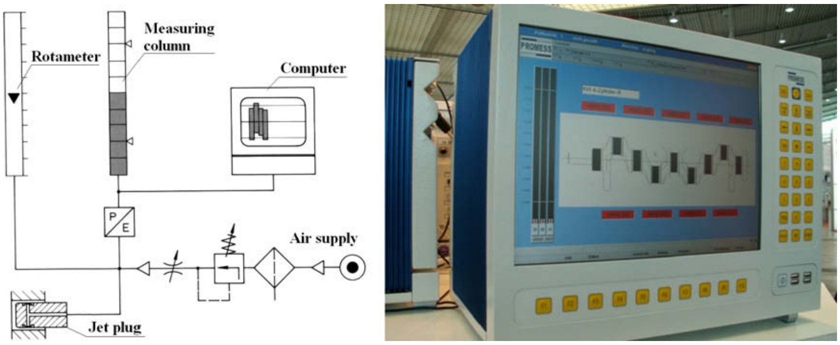

Fig. 7. Pressure/electronic converter in the measurement system [6] (left) and the industrial computer able to receive measuring signal from several converters (right).

This type of pressure/electronic (or air/electronic) converters may be constructed as an additional devices, or built into the air gauging system. For example, Mercer company delivers such a converter either as a built-in part of the dimensional measurement system (Fig. 8) [7], or as a single device.

Many companies which product the air gauges for dimensional measurement, deliver the pressure/electronic converters as well. The advantage of the converters is that the output signal generated by the inductive sensor could be further processed together with similar signals from other sensors, e.g. inductive ones. For instance, Marposs company delivers air/electronic converters (Fig. 9 left) which contain the regulators of sensitivity and zero point, and generate a signal for further processing with a fully comprehensive Industrial PC and Data Acquisition System. Three most common values of pneumatic sensitivity (0.5, 1.0 and 1.5 kPa/μm) could be preselected, while the other values dependent on the applied nozzles diameters could be set. The converter is designed to work with a device called E9066 Flat Panel (Fig. 9 right).

The E9066 Flat Panel Workstation is equipped with Quick SPC software package, enabling performance for real-time data acquisition and measuring applications, industrial process control, real-time SPC and closed-loop machine tool control. Its standard interface could receive a signal from up to 64 analog sensors (LVDT, HBT, strain gauge) made by Marposs or any other company. Similarly, Mahr company [9] delivers the multi-gaging computers and intelligent measurement interface systems able to integrate inductive probes, incremental probes, digital measuring instruments and pneumatic measuring devices (trough air/electronic

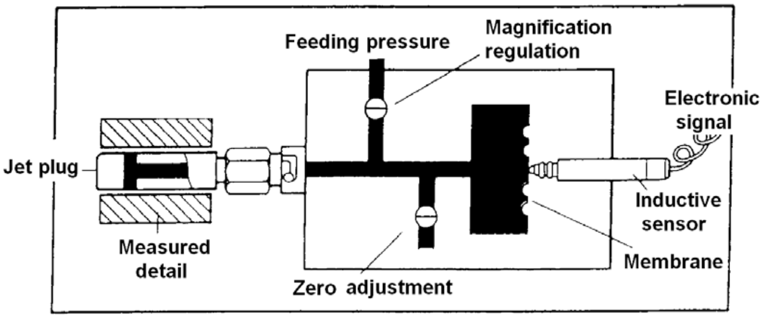

Fig. 8. Pneumatic dimensional measurement system with electronic output [7].

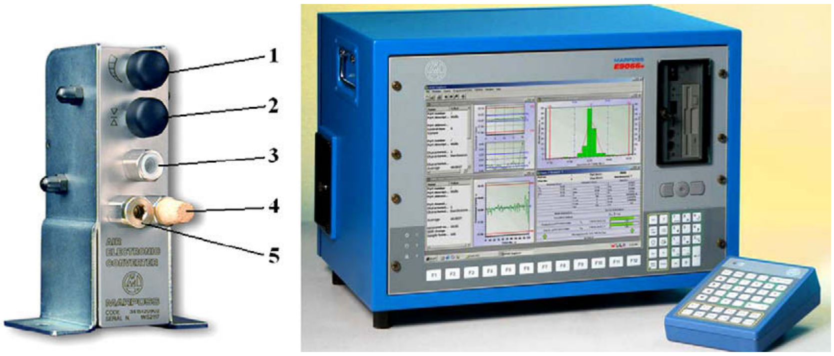

Fig. 9. Air/electronic converter (left) and a PC-based industrial system E9066N (right) [8].

converters). Millitron is a process computer which enables to measure and evaluate several values simultaneously. The measured values could be used for statistical Process Control according to QS 9000. The devices provide the data export in ASCII or EXCEL formats. The Millimar interface system acts as a signal transformer between sensors and the electronic measurement data processing system. It provides also an equation editor and statistical functions like N, x-bar, S, Xmax, Xmin, Range.

It must be noted that some companies do not reveal the operating principle of the applied transducers or converters. For example, Etamic delivers the solid state TPE99 Air to Electronic converter (Fig. 10), used with a gaging system, able to perform high precision measurement. It provides the measurement in various ranges from ±5 μm to ±120 μm with accuracy ca. 0.5% of the measuring range [10]. Its operating principle is protected by two International Patents, and is not even mentioned in the available publications.

4. Air gauges combined with piezoresistive pressure sensors

Several years ago, the investigations on the air gages integrated with the piezoresistive pressure transducers were started in the Division of Metrology and Measurement Systems (Poznan University of Technology). This type of transducers are based on silicon crystal that underwent a pressure through small diaphragm (Fig. 11). Under the pressure, crystal thickness changes by a small amount and it sets up a charge described by following formula [4]:

Fig. 10. TPE99 Air to Electronic converter [10].

$$q = K_q p_a A, \tag{2}$$

where A is the area of the electrode, p_a is the pressure acting over electrode area A and K_q is the crystal charge sensitivity dependent on material.

Piezoelectric sensor is very sensitive to the temperature changes that cause zero drift. In order to avoid such an effect, it is customary to connect parallel and series resistors to the bridge scheme. The silicon crystal is a part of a sensor chip glued to the ceramic plate with thickfilm resistors shown in Fig. 11 above. The output signal is amplified.

Having much smaller dimensions than bellows and membranes, piezoresistive sensors have got much better dynamical properties: their response time, according to the technical specifications, does not exceed 0.1 ms [11]. Unlike most elastic pressure sensors, such a transducer could be placed in the air gauge applications very close to the measuring nozzle [12], directly into the measuring head (jet plug) as it is shown in Fig. 12. Hence, the transmission effect is reduced down to minimum. The simplified response equation of the compressible gas could be expressed by formula [4]:

$$\frac{4L\rho V}{\pi E_m d^2}\ddot{p}_m + \frac{128\mu L V}{\pi E_m d^4}\dot{p}_m + p_m = p_a(t), \tag{3}$$

where L is the length of the transmission tube, d is the diameter of the transmission tube, p_m is the measured pressure in an internal dead volume V of the transducer, p_a is the applied pressure and E_m is the fluid bulk modulus of elasticity.

It is seen that the time constant is proportional to the L/d^4 ratio, as well as to the dead volume V of the transducer. Combined with small volume of the air gauge measuring chamber, the dynamical properties of the air gaging systems could be substantially improved. The time constant of the device could be reduced down to the value of 0.011–0.025 s [13], varying dependent on the configurations of the air gauges. When long

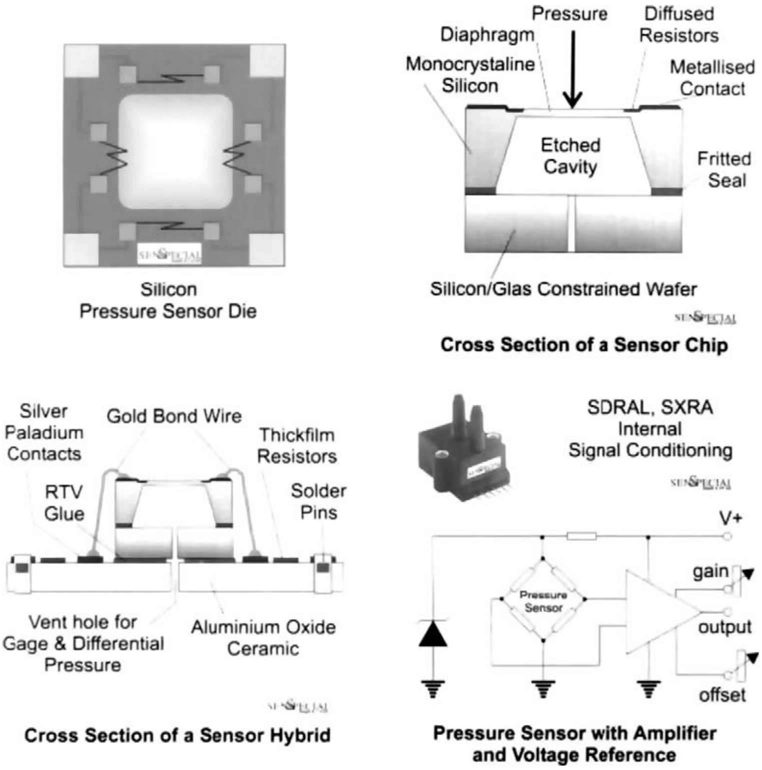

Fig. 11. Piezoresistive pressure sensor [11].

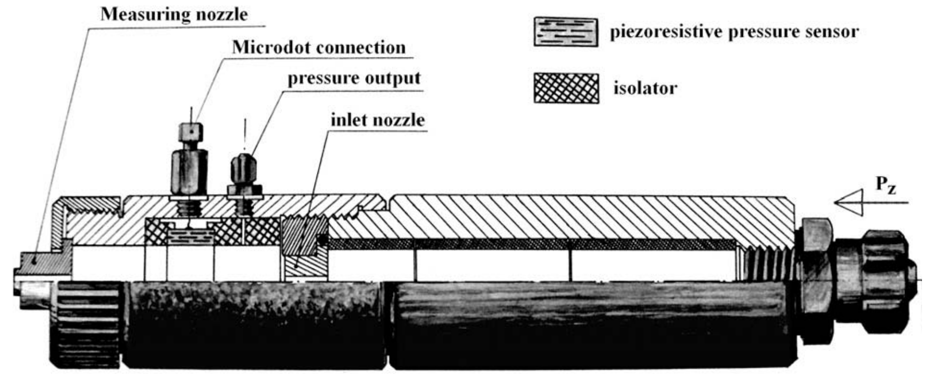

Fig. 12. Experimental model of the air gauge with built-in piezoresistive pressure sensor.

transmission line is used, the setting time could reach 0.3 s (1 m hose) and even 0.5 s (2 m hose), as it is specified for piezo air/electronic converter for Millimar S1840PE [9].

However, the piezoresistive sensor placed directly into the measuring chamber of air gauge enables to minimize response time. Close to the piezoresistive pressure sensor (Fig. 12), the hole for the pressure output was made, leading to the distanced pressure transducer. The feeding tube between the distanced transducer and the measuring chamber was 30 mm long, with the diameter of 2 mm. As a result, the response time went two times shorter, as it is seen in Fig. 13 where the graphs of step response registered by both sensors are presented.

The mathematical model was based on the second critical parameters [12]. The mass flow ratio $m_{ps}(t)$ for the flapper-nozzle area is described as a maximal mass flow multiplied by coefficients of loss:

$$m_{ps}(t) = \alpha_{kr2,ps}\delta_{ps}\underset{t\max,ps}{\dot{m}}, \tag{4}$$

where $\alpha_{kr2,ps}$ is the second critical parameter for the flapper-nozzle valve and $\dot{m}_{t\max,ps}$ is the maximal theoretical mass flow through the flapper-nozzle valve,

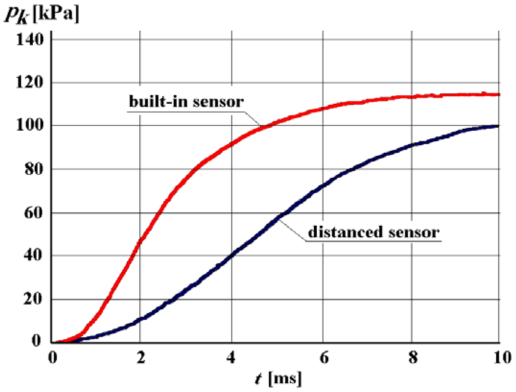

Fig. 13. The step response of the air gauge registered simultaneously by two sensors.

$$\delta_{ps} = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa+1}} \sqrt{\frac{\kappa+1}{\kappa-1}} \xi_{ps}^{\frac{1}{\kappa}} \sqrt{1-\xi_{ps}^{\frac{\kappa-1}{\kappa}}}, \tag{4a}$$

$$\xi_{ps} = 1 - \frac{1-\beta_{kr1}}{1-\beta_{kr2,ps}}\left(1-\frac{p_a}{p_k}\right), \tag{4b}$$

$$m_{t\,\max,ps} = \sqrt{\kappa\left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{\kappa-1}}} \sqrt{\frac{1}{R} A_{ps} \frac{p_k}{\Theta_z}}, \tag{4c}$$

$\beta_{kr1}, \beta_{kr2,ps}$ the first and second critical pressure ratios ($\beta_{kr1} = 0.528$) and A_{ps} is the flow-through surface of the flapper-nozzle valve.

Similarly, the mass flow through the inlet nozzle is calculated, and the condition of the mass continuity must be fulfilled. Table 1 presents the results of experimental investigations (e) and of calculations (c) of setting time $t_{0.95}$ and time constant τ for the air gauge with measuring nozzle diameter $d_p = 2.060$ mm combined with three different inlet nozzles d_w. It could be expected that application of concurrent mechanistic and statistical model [14] would provide the calculated results closer to the experimental one.

According to the technical data [11], linearity and hysteresis of the piezoresistive transducers lay in the range of ±0.2%, maximally ±0.5% of its maximal indication. However, piezoresistive transducers did not find a wide application in the air gauge systems (or, at least, some companies apply them but do not reveal this fact). Nevertheless, some successful attempts were made to include this type of transducer into the air gauging system. One of the most worthy attention is a series of devices called PNEUTRONIK [15] produced by Institute of Advanced Technology (Poland) and presented in Fig. 14. They are designed for measurement laboratory (especially types B25 and B50) and the production lines (especially C2K). In all devices of this type, two units may be distinguished (a pneumatic and an electronic ones shown in Fig. 15).

Table 1
Parameters of the step responses of the model and actual sensor [12].

d_w [mm]	Calculated (c)		Experimental (e)	
	$t_{0.95}$ (c) (ms)	τ (c) (ms)	$t_{0.95}$ (e) (ms)	τ (e) (ms)
1.002	52.0	16.8	46.3	15.0
1.200	27.4	8.6	26.5	7.4
1.545	17.2	6.1	14.6	5.3

Fig. 14. Devices B50 (left) and C2K (right) of PNEUTRONIK series.

Pneumatic unit of the device is a typical back-pressure air gauge with filters, magnification regulator, measuring chamber and the measuring head of any type. The measurement of pressure p_k is conducted by the piezoresistive transducer, and the result of measurement is forwarded into the microprocessor. Unlike the most of available in the market pneumatic gages, PNEUTRONIK has electronic correction of zero point instead of typical bleeding valve. This causes some savings of the pressured air and, hence, of the exploitation costs.

The processor could generate direct indication of back-pressure recalculated into μm. In some solutions (like in B50 shown in Fig. 14 left), the electronic signal is converted into mechanical rotation of the pointer. If programmed, a control or warning signal could be sent by processor, achieved data are recorded or transmitted into outer computer or printer. Input and keyboard units enable a dialogue between the system and the operator. In some solutions. The adjustment of zero point, tolerances and control signals is available from the keyboard (front panel keypad or interactive LCD screen). Moreover, the characteristics of particular measuring could be recorded and recalled later, without need of new adjustment which saves an operator's time. The memory can bear data on a number of measuring heads, varying dependent on the type of device. The device may cooperate with any jet plug head, even with ones delivered by other producers or made individually for the particular measurement task. The calibration characteristics of the chosen jet plugs could be recorded and later recalled, without a need of new adjustment after exchange of measuring heads.

For the analysis of achieved measurement data, the program PNEUSTAT could be installed into the outer computer. It is able to calculate a range of the statistical parameters for data transmitted form the PNEUTRONIK, and to correlate them with the production identification (date, working shift, week or particular time period for analysis). It is possible to calculate process capacity coefficients C_p and C_{pk} and to chart $\bar{X} - R$ graph, as well as to calculate the machine capacity coefficients C_m and C_{mk}. A range of other data important in the Statistical Process Control and Quality Management could be calculated.

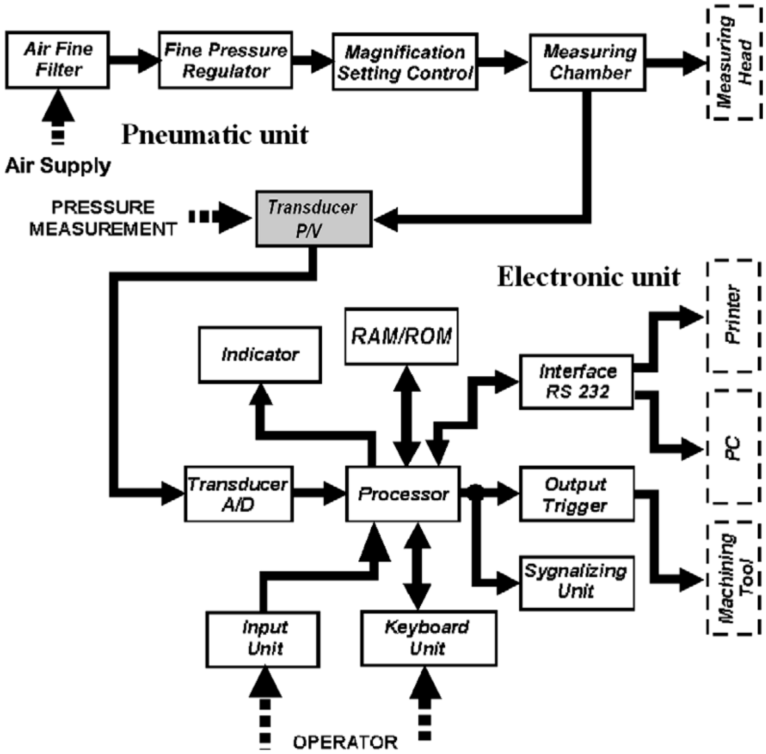

Fig. 15. The pneumatic and electronic units of PNEUTRONIK measuring device.

The systems of measurement and signal processing ensure high resolution of the measurement, and the accuracy on the level of ±0.4 μm. It should be noted that the uncertainty of the dimensional measurement with the air plug may be affected by the conditions of the air outflow [16]. For example, the reduction of the measuring nozzle outer diameter could radically change the character of pressure fluctuations in the measuring chamber causing the reduction of the signal dispersion. As a result, the uncertainty of air gauge may become several times smaller, down to values of ±0.05–0.1 kPa which correspond with ±0.02–0.1 μm dependent on the actual multiplication [17].

5. Multipoint linearization

Linearity is one of the most important characteristics of the measurement system. It should be noted that typical air gauge requires two setting masters in order to determine basic points of its characteristics. Nowadays, an interesting trend appears: to enable the adjustment with only one setting master, like in Dimensionair [9] or Pneutamic [18] devices. Unlike them, PNEUTRONIK allows to perform linearization based on three or more points (some types of device accept even up to 16 setting points). This way the linearity error may be reduced, and the measuring range may be widened. However, for that purpose more setting masters should be prepared which may rise the expenses too high.

In Fig. 16, there are graphs of static characteristics of air gauge $p_k = f(s)$ and its sensitivity $K = f(s)$. The measuring range z_p could be assumed between $s_1 = 112\ \mu\text{m}$ and $s_2 = 294\ \mu\text{m}$, because its linearity error in this range does not exceed $\delta_{\max} = 1.0\%$.

The way of calculation of linearity error has been described in [15] and was performed as following:

$$\delta_{\max} = \frac{|\Delta p_{ki\max}|}{p_{k\max} - p_{k\min}} \times 100\%, \tag{5}$$

where p_{ki} is the value of air pressure in the measuring chamber, measured for certain clearance s_i, $p_{k\max}$ and $p_{k\min}$ is the values of maximal and minimal measuring pressure for proposed measuring range z_p and $\Delta p_{ki\max}$ is

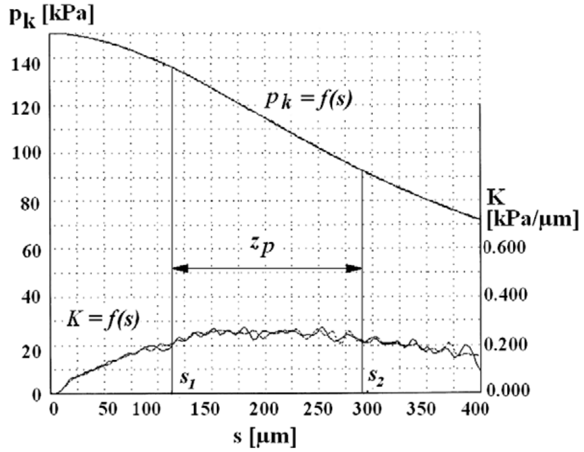

Fig. 16. The example of the analyzed characteristics.

the maximal difference between calculated $\hat{p}_{ki}$ and measured p_{ki} pressure for each clearance s_i. The way of calculation of Δp_{ki} is:

$$\Delta p_{ki} = p_{ki} + \hat{p}_{ki}, \tag{6}$$

where $\hat{p}_{ki} = a_0 + a_1 s_i$ is the calculated using the coefficients of estimated linear function a_0 and a_1.

However, the $\delta_{\max}$ error is calculated in relation to the estimated Minimum Square Line, while in reality linearization is based on setting masters corresponding to first and last points s_1 and s_2 of the characteristics. Related to this line, the linearity error is much larger $\delta_{\max} = 2.9\%$. However, when two additional setting masters are introduced, corresponding with slots 172 and 234 μm, the three parts of the characteristics would have non-linearity, respectively, $\delta_{\max 1} = 1.1\%$,$\delta_{\max 2} = 0.7\%$ and $\delta_{\max 3} = 0.9\%$. Further, if it is divided into five equal part with 6 setting masters, the maximal non-linearity could be broken down to 0.6%, and even down to 0.3% with 10 setting masters. It could be assumed from series of simulations and experimental measurements, that the linearity error of the system adjusted by 5 or 6 setting masters could be as low as 10–15% of the linearity error gained from two point adjustment, but further increase of the number of setting masters could not improve the results more than 1–3%.

Taking into consideration the costs of the accurate setting masters, it is worthy to perform thorough analysis of the static characteristics of jet plugs. On the basis of that analysis, it is possible to divide the characteristics presented in Fig. 16 into three non-equal parts with maximal linearity error $\delta_{\max} = 0.8\%$. It is even better result than for Minimum Square Linearization of the whole characteristics, and almost as good as for 6 setting masters.

To sum up, the multipoint linearization is very important concerning the Quality Control Systems, because it enables to reduce linearity of pneumatic dimensional measurement device through the easy and routine adjustment process.

6. Conclusions

Nowadays, the industrial production system requires of the measurement system not just accuracy and reliability of measurement, but also ability to collect and to process measurement data. Pneumatic devices for dimensional measurement could be successfully applied in Quality Management Systems because they ensure quick, accurate and relatively cheap measurement, and the gained pressure signal could be easily converted into electronic signal for further data processing. Though most of the available pneumatic devices are based on the traditional membrane-type pressure sensors, there are various methods to gain electronic signal directly from the pressure measurement (through secondary transducer element) or from air/electronic converters included into the measurement line. However, elastic measuring elements has poor dynamical properties, mostly because of relatively large dimensions of internal dead volume.

On the other hand, devices based on piezoresistive pressure sensors provide short setting times and electric output signal. In the PNEUTRONIK devices, the built-in electronic unit based on the independent microprocessor converts the analog signal to digital one, process it and enables to control all needed functions of the measurement system. In other systems those functions could be performed in outer processors and interface systems. The output signal could be used as a control (switching) signal, as a warning signal for the operator, it could be recorded and included into statistical analysis and so on. Additionally, if the piezoresistive transducer is placed directly in the measuring chamber of the air gauge, dynamical properties could be further improved.

Important trend should be noted in the field of air gauge linearization. In many devices, the adjustment process tends to be reduced down to one setting master only, but in the others, it became possible to use more than two setting masters and to improve the linearity substantially. The last one seems to be more promising because of non-linear characteristics of the back-pressure itself.

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